FERMILAB-CONF-07-50-T

Weak Mixing and Rare Decays in the Littlest Higgs Model

William A. Bardeen

Theoretical Physics Department

Fermilab, MS 106, P.O. Box 500

Batavia, IL 60510

(Dated: March 15, 2007)

Little Higgs models have been introduced to resolve the fine-tuning problems associated with the stability of the electroweak scale and the constraints imposed by the precision electroweak analysis of experiments testing the Standard Model of particle physics. Flavor physics provides a sensitive probe of the new physics contained in these models at next-to-leading order.

I. INTRODUCTION

The Standard Model has been extraordinarily successful in describing all known phenomena of particle physics with the possible exception of the astrophysical evidence for dark matter. Precision experiments including the results from LEP, the Tevatron and the B-factories have confirmed detailed predictions of the Standard Model and have placed strong constraints on new physics associated with the electroweak scale. Flavor changing processes such as weak mixing and neutral current processes in rare decays are strongly suppressed in the Standard Model and provide a unique window on new physics at scales much above the electroweak scale.

Despite the success of the Standard Model, there remain puzzles concerning the mechanisms that determine parameters of the SM which must be finely adjusted to agree with experiment. These include the theta angle of strong CP violation, the Higgs mass term which determines the electroweak scale and the net vacuum energy density which may be responsible for the dark energy inferred from astrophysical data. In particular, the Higgs mass term gets large radiative corrections from Standard Model processes which would normally be expected to destabilize the electroweak scale. If new physics is introduced to stabilize these radiative corrections, then there can be a tension between the SM fits to precision electroweak data and the new physics contributions.

II. THE LITTLEST HIGGS MODEL

Little Higgs models [1, 2] are based on the dynamics of pseudo-Nambu-Goldstone bosons where the Higgs mass term is protected from radiative corrections by the existence of new symmetries that are dynamically broken. In the absence of additional explicit breaking of these new symmetries, the physical Higgs boson remains massless [3]. The Higgs mass will be protected from the quadratically divergent radiative corrections if the explicit symmetry breaking occurs collectively, ie. two or more symmetry breaking terms must be present in order to generate a mass for the physical Higgs boson.

The main ingredients of Little Higgs models are an extended electroweak gauge group, $G_1 \otimes G_2 \rightarrow$SM, which is embedded in a larger global symmetry with dynamical symmetry breaking, and an extended top quark sector needed to accommodate the observed top quark mass. The global symmetries are broken collectively and the physical Higgs boson is a pseudo-Nambu-Goldstone boson. There are typically three important scales in Little Higgs models, Λ ($10 \rightarrow 30$ TeV) – the scale of new dynamics and the effective cutoff, f ($1 \rightarrow 3$ TeV), $f \sim \Lambda/4\pi$ – the scale of dynamical breaking of the global symmetries and the mass scale of the new particles used to cancel the quadratic divergences, and v (175 GeV), $v \sim f/4\pi$ – the electroweak scale and the mass of the SM Higgs boson, the SM gauge bosons and the top quark.

The Littlest Higgs model [4] is based on the Nambu-Goldstone bosons of the coset space of $SU(5)/SO(5)$. The gauge boson dynamics is based on the $[SU(2) \otimes U(1)]_1 \otimes [SU(2) \otimes U(1)]_2$ subgroup of $SU(5)$ which is broken to the electroweak gauge group, $(SU(2) \otimes U(1))_{\rm SM}$, at the scale f. Four of the fourteen Nambu-Goldstone bosons are absorbed by the heavy gauge bosons, $(W_H^\pm, Z_H^0, A_H)$. Of the ten remaining Nambu-Goldstone bosons, six form a complex triplet $(\Phi^{++}, \Phi^+, \Phi^0)$ and acquire a mass of order f, and four form a complex doublet (H^+, H^0) corresponding to the usual Higgs field of the Standard Model. The top quark sector is also modified. A heavy vector-like top quark is needed in addition to the Standard model top quark in order to cancel the quadratic divergences associated with top quark loops.

In the Littlest Higgs model described above, the heavy gauge bosons mix with the light SM gauge bosons at tree level. These mixings can result in significant modifications to the predictions of the Standard Model that are highly constrained by precision electroweak measurements. These constraints will force the symmetry breaking scale, f, to be large [5]. However, a large scale for f can reintroduce issues associated with the fine-tuning of the Higgs mass parameters.

This tension can be relaxed through the introduction of a new symmetry, T-parity [6], which prohibits the mixing between the heavy and light gauge bosons. The heavy gauge bosons and the complex triplet scalars are odd under T-parity while the complex doublet Higgs field and the Standard Model gauge bosons are even. The top quark sector must also be modified to preserve T-parity. Since all interactions are to be invariant under T-parity, the lightest odd parity particle will be a dark matter candidate. The precision electroweak constraints for the Little Higgs model with T-parity have been carefully analyzed [6] and lower scales for the new physics can be tolerated with less tension with the fine-tuning of the Higgs mass parameters.

III. FCNC PROCESSES IN THE LITTLEST HIGGS MODEL

Flavor-changing processes are highly suppressed in the Standard Model and, therefore, provide a unique opportunity for the exploration of new physics contributions. Flavor physics has long been focus of Andrzej Buras and his collaborators. I will report on some of their conclusions concerning weak mixing and flavor-changing neutral current processes in the Littlest Higgs model with and without T-parity. The reader is referred to the original papers for detailed predictions and specific results.

Weak mixing amplitudes for $\Delta S = 2$ and $\Delta B = 2$ processes are described by effective weak Hamiltonians involving appropriate four-fermion operators with coefficient functions that are sensitive to the short distance physics. At leading order, the coefficient functions are determined by box diagrams involving both Standard model particles and the new heavy states of the Littlest Higgs model. The calculations can be made in unitary gauge where only physical particles are taken into account. Single box diagrams in unitary gauge are divergent but the divergences all cancel at one loop due to the GIM mechanism.

For the Littlest Higgs model without T-parity, Buras et al.[7, 8] find that the new physics contributions to ΔM_s, ΔM_d and ε_K are all positive. This implies a suppression of $|V_{td}|$ and of the angle γ in the unitarity triangle as well as an enhancement of ΔM_s relative to the Standard Model expectations. If the scale f is as small as 1 TeV, the effects amount, at most, to 15-20% corrections and decrease below 5% for $f > 3$–4 TeV as required by the precision electroweak constraints. Contributions of the charged scalars, $\Phi^{\pm}$, turn out to be negligible.

Rare decays are also described by an effective weak Hamiltonian which includes both box diagrams and flavor-changing neutral current processes. In the Littlest Higgs model without T-parity there is considerable mixing between the new heavy states and those of the Standard Model. In unitary gauge, the analytic results can be decomposed into six classes of diagrams. Custodial symmetries are broken at $O(v^2/f^2)$ in contributions at next-to-leading order.

The corrections to the coefficient functions for rare decay processes are at most 15% for a scale $f \sim O$(2–3 TeV). The amplitudes for $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, $B_{s,d} \to \mu^+\mu^-$ and $B \to X_{s,d}\nu\bar{\nu}$ are all calculated[8] but are hard to distinguish from the Standard Model. There are also very small corrections ($\sim 4\%$) to the branching ratio for $B \to X_s\gamma$. The new physics contributions to rare decays are generally suppressed by the large scale required for f due to the lack of custodial symmetry in the Littlest Higgs model without T-parity.

A novel feature of this calculation is the presence of residual ultraviolet divergences that are found in the amplitudes for rare decay processes at order (v^2/f^2). These residual divergences are not an artifact of unitary gauge but are also present in calculations using renormalizable gauges such as Feynman gauge. The divergences represent a true sensitivity to the ultraviolet completion of the Littlest Higgs model.

These divergences are very analogous to the renormalization of G_A in a chiral quark model where chiral loops generate a log divergent contribution to G_A in the nonlinear version of the theory. The linear quark-sigma model is renormalizable and the renormalization of G_A is finite. In this case, the cutoff scale in the log divergent term is replaced by the mass of the scalar partner to the pion and no other divergences survive.

In the calculations of the FCNC processes described above, Buras et al.[8] estimate the divergent terms by using the scale, $\Lambda = 4\pi f$, the ultraviolet cutoff scale of the Littlest Higgs model. Finite corrections could be added reflecting additional "Leutwyler terms" in the effective field theory description of the dynamics.

IV. FLAVOR PHYSICS IN THE LITTLEST HIGGS MODEL WITH T-PARITY

To avoid the strong precision electroweak constraints, Cheng et al.[6] introduce a T-parity symmetry to the Littlest Higgs model. The presence of the custodial symmetry in this model allows for a lower scale f for the new physics and a more realistic solution to the tension between the Higgs fine-tuning problem and the precision electroweak constraints. Hubisz et al.[9] were the first to study flavor physics and the potential for new physics in weak mixing processes in the Littlest Higgs model with T-parity. These processes were also studied by Buras et al.[10] and extended to FCNC processes and rare decays [11]. The lower scales for the new physics in these models could imply much larger effects for flavor changing processes than were found in the previous analysis of the models without T-parity.

In the Littlest Higgs model with T-parity, the Standard Model particles have even T-parity while the heavy gauge bosons and Higgs triplet scalars are odd under T-parity. To incorporate the T-parity symmetry, the fermion sector becomes more complex [6] with additional fermions having both even and odd T-parity.

Buras et al.[11] consider two scenarios, one with a degenerate mirror fermion spectrum corresponding to a minimal flavor violation (MFV) scenario and one with a mirror fermion hierarchy different from CKM corresponding to a non-MFV scenario. A wide range of parameter space is explored for the impact of the new physics contributions on predictions for weak mixing, CP asymmetries and rare decays.

Some general conclusions are possible. There are now regions where the B_s oscillation parameter, ΔM_s, is smaller than the Standard Model value in closer agreement with the recent Tevatron measurements [12]. The $\sin 2\beta$ "problem" can be solved, ie. the difference between the value 0.786 ± 0.052 from tree-level decays and the value 0.675 ± 0.026 from the CP asymmetries [13]. The two processes actually measure somewhat different angles in the Littlest Higgs model. The semileptonic CP asymmetry, A^s_{SL}, can be enhanced by a factor of 10–20 and A^d_{SL} by a factor of 3 above the SM predictions. The CP asymmetry, $S_{\psi\phi}$, can be as high as 0.3 compared to the Standard Model value of 0.04. The rare decays of neutral and charged K-mesons to neutrinos can be enhanced by an order of magnitude over the SM predictions. In fact there are two branches of parameter space, one where the branching ratio for $K^+ \to \pi^+ \nu\bar{\nu}$ can be greatly enhanced but the decay $K_L \to \pi^0 \nu\bar{\nu}$ is SM-like and one where $K_L \to \pi^0 \nu\bar{\nu}$ can be greatly enhanced with only modest enhancements of $K^+ \to \pi^+ \nu\bar{\nu}$. I refer to the original papers [10, 11] for detailed plots.

V. CONCLUSIONS

Little Higgs models offer a novel approach to resolving the tension between the fine-tuning of the Higgs mass parameter and the constraints of precision electroweak experiments. The Littlest Higgs model is a specific realization of these models which can address all aspects of physics from the electroweak scale to scales of order 10–30 TeV. Flavor physics is highly constrained in the Standard Model by the CKM structure of flavor-changing processes.

Weak mixing and rare decay processes provide sensitive probes of the new physics contained in the Littlest Higgs model. Because of the lower new physics scales possible in the Littlest Higgs model with T-parity, large flavor-changing effects are possible in some regions of parameter space providing specific opportunities for probing physics beyond the Standard Model.

A novel aspect of these calculations is the presence of log divergent contributions to the flavor-changing Z-boson vertex. These contributions are gauge invariant and signal an additional sensitivity of flavor physics to the ultraviolet completion of the Littlest Higgs model.

Acknowledgements

Talk presented at the 2006 International Workshop on The Origin of Mass and Strong Coupling Gauge Theories held November 21-24, 2006 at Nagoya, Japan. I would like to thank Koichi Yamawaki and the other members of the Organizing Committee for their hospitality and for inviting me to participate in SCGT2006.

The transparencies for this talk were prepared by A. Poschenrieder (Technical University, Munich) based on his lecture at the Ringberg Workshop on Heavy Flavor Physics, October, 2006.

Fermilab is operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

---

[1] N. Arkani-Hamed, A. Cohen, H. Georgi, Phys.Lett. B513:232(2001); N. Arkani-Hamed, A. Cohen, T. Gregoire and J. Wacker, JHEP 0208:020(2002); N. Arkani-Hamed, A. Cohen, E. Katz, A. Nelson, T. Gregoire and J. Wacker, JHEP 0208:021(2002).

[2] N. Arkani-Hamid, A. Cohen, E. Katz and A. Nelson, JHEP 0207:034(2002); I. Low, W. Skiba and D. Smith, Phys.Rev. D66:072001(2002).

[3] D. Kaplan and H. Georgi, Phys.Lett. B136:183(1984); D. Kaplan, H. Georgi and S. Dimopoulos, Phys.Lett. B136:187(1984).

[4] N. Arkani-Hamed, A. Cohen, E. Katz and A. Nelson, JHEP 0207:034(2007).

[5] C. Csaki, J. Hubisz, G. Kribs, P. Meade and J. Terning, Phys.Rev. D67:115002(2003); C. Csaki, J. Hubisz, G. Kribs, P. Meade and J. Terning, Phys.Rev. D68:035009(2003); M.C. Chen and S. Dawson, Phys.Rev. D70:015003(2004); Z. Han and W. Skiba, Phys.Rev. D72:035005(2005).

[6] H.C. Cheng and I. Low, JHEP 0309:051(2003); H.C. Cheng and I. Low, JHEP 0408:061(2004); I. Low, JHEP 0410:067(2004); J. Hubisz and P. Meade Phys.Rev. D71:035016(2005); J. Hubisz, P. Meade, A. Noble and M. Perelstein, JHEP 0601:135(2006); M. Asano, S. Matsumoto, N. Okada, and Y. Okada, arXiv:hep-ph/0602157.

[7] A. Buras, A. Poschenrieder and S. Uhlig, Nucl.Phys. B716:173(2005); S. Choudhury, N. Gaur, A. Goyal and N. Mahajan, Phys.Lett. B601:164(2004); M. Blanke, A. Buras, A. Poschenrieder, C. Tarantino, S. Uhlig and A. Weiler, JHEP 0612:003(2006).

[8] A. Buras, A. Poschenrieder, S. Uhlig and W. Bardeen, JHEP 0611:062(2006).

[9] J. Hubisz, S. Lee and G. Paz, JHEP 0606:041(2006).

[10] M. Blanke A. Buras, A. Poschenrieder, C. Tarantino, S. Uhlig and A. Weiler, JHEP 0612:003(2006).

[11] M. Blanke, A. Buras, A. Poschenrieder, S. Recksiegel, S. Tarantino, S. Uhlig and A. Weiler, JHEP 0701:066(2007); M. Blanke, A. Buras, B. Duling, A. Poschenrieder and C. Tarantino, TUM-HEP-657-07 (2007).

[12] A. Abulencia et al. [CDF Collaboration], Phys.Rev.Lett. 97:242003(2006); V. Abazov et al. [D∅ Collaboration], Phys.Rev.Lett. 97:021802(2006).

[13] M. Bona et al. [UTfit Collaboration], JHEP 0603:080(2006); M. Bona et al., Phys.Rev.Lett. 97:151803(2006); J. Charles et al. [CKMfitter Group], Eur.Phys.J. C41:1(2005).